The heavy-ion time-of-flight spectrometer HiToF*

Hao-Rui Wang,[1] Cheng-Jian Lin,[1,†] Nan-Ru Ma,[1] Lei Yang,[1,‡] Feng Yang,[1] Hui-Ming Jia,[1] Pei-Wei Wen,[1] Tian-Peng Luo,[1] Chang Chang,[1] Hai-Rui Duan,[1] Song-Xian Zhu,[1] Zhi-Jie Huang,[1] Cheng Yin,[1] Zhi-Jie Huang,[1] Ze-Rui Fan,[1] Ling-Yi Fu,[1] Hui-Yan Li,[1] Shao-Wen Mo,[1] Hao Lu,[1] and Chen-Xu Wu[1]

[1] *China Institute for Atomic Energy, 102413 Beijing, China*

A heavy-ion time-of-flight spectrometer called HiToF with magnet focusing accomplished by quadrupole triplet lens has been constructed at Beijing Tandem Accelerator National Laboratory, mainly for studies of multi-nucleon transfer reactions at energies near the Coulomb barrier. The spectrometer is equipped a rotating chamber with a diameter of 40 cm and can be rotated in a large angular range from -40° to 160°. The length from target to the focal plane is 2.7 m, enabling high-precision time-of-flight measurements by two micro-channel-plate detectors with 1.9 m apart and typical time resolution of 120 ps. A multi-sampling position-sensitive ionization chamber for $\Delta E - E$ measurement is placed on the focal plane, which offers $\Delta Z/Z$ resolution of $\frac{1}{50}$. The setup provides a maximum solid angle $\Delta\Omega$ = 20 msr. An experiment of ^{32}S + ^{90,94}Zr at the beam energy of 135 MeV was performed to test the performance. The projectile-like ions were identified clearly with the mass resolution $\sigma = 0.2$ amu. Results show that the HiToF spectrometer is a powerful setup for studying the mechanism of heavy-ion reactions at low-energies.

Keywords: Time-of-flight spectrometer, Heavy-ion, Multi-nucleon transfer reaction, Quadrupole triplet lens

I. INTRODUCTION

Multi-nucleon transfer (MNT) is considered as a promising method for the production of neutron-rich heavy or superheavy nuclei and has been studied in the field of low-energy nuclear reaction for several decades. Despite significant theoretical and experimental efforts, the mechanism of MNT has not been so clear yet due to the complex phenomena involving the transfer and/or transport of numerous nucleons [1, 2].

Due to the intricacies of the reaction mechanisms involved, the measurement of MNT products requires improved precision, placing higher demands on the equipment: i) good mass (A) and charge (Z) identifications for validation of various reaction channels; ii) a large acceptance for detection of rare products that are far from the projectile or target, considering the steep decrease in cross sections with an increasing number of transferred nucleons; iii) a good energy resolution for distinction of a huge number of energy levels populated in a specific reaction channel.

Several detection techniques have been developed for particle identification, such as the measurement of time-of-flight (ToF) with a known distance of flight. The relative uncertainty is drastically ruduced with a long flight distance. As a mature method, the E-ToF technique, which measures energy and ToF simultaneously, has been widely used in studies on transfer reactions at energies near the Coulomb barrier [3]. The mass resolution, determined by energy and ToF measurements, reaches $\sigma = 0.2$ amu. For binary reactions, the kinematic coincidences technique is an effective method to enhance energy and mass resolution through methods such as simultaneous measurements of ToF of projectile-like ions and correlated scattering angles [4].

To make further investigation of the mechanism of MNT reactions, a ToF spectrometer for heavy ion reactions, called HiToF, was constructed at the HI-13 tandem accelerator of Beijing Tandem Accelerator National Laboratory. Its design resembles the spectrometer of PISOLO [5] at Laboratori Nazionali di Legnaro but with a focusing system including quadrupole triplet lens. The maximum solid angle covered by HiToF reaches 20 msr. HiToF is equipped with two micro-channel-plate detectors dedicated to time-of-flight measurement and a specially designed ionization chamber for energy measurement and charge identification on the focal plane. A test experiment has been recently conducted successfully, laying a solid foundation for the further investigation of multi-nucleon transfer reactions.

The paper is organized as follows. Section II describes the detection systems and ion optical elements; Section III presents the recent results of the ^{32}S + ^{90,94}Zr test experiment; Section IV summarizes the results and our conclusions.

II. SPECTROMETER

The HiToF spectrometer mainly consists of an adjustable detection system and an ion-optical system. It is connected to a steal-tape sealed rotating chamber with a diameter of 40 cm. The spectrometer can rotate with the chamber as a center, covering an angular range from -40° to 160°. A schematic view of the spectrometer is persented in Fig. 1.

A. The detection system

The detection system includes a ToF measurement that mainly uses two micro-channel plates (MCP1 and MCP2) and an energy measurement using a multi-sampling position-sensitive ionization chamber (IC) installed at the focal plane.

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† Corresponding author, cjlin@ciae.ac.cn

‡ Corresponding author, yang˙lei@ciae.ac.cn

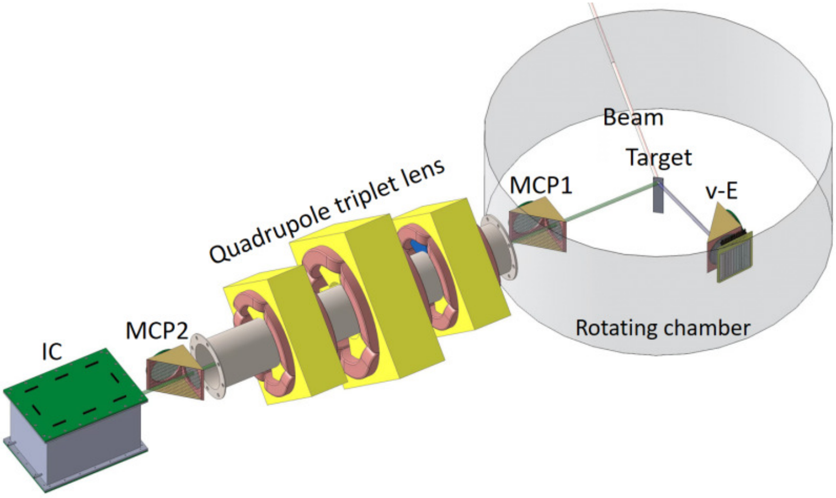


Fig. 1. (Color online) Schematic view of the HiToF spectrometer.

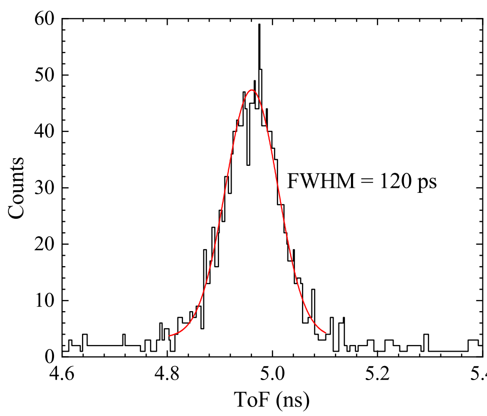


Fig. 2. (Color online) ToF spectrum obtained by a α source in a short flight distance of 5 mm.

A v-E detector including an MCP and a double-sided silicon-strip detector (DSSD) is also installed at the complementary angle in the rotating chamber for the velocity and energy measurements of target-like particles.

The ToF measurement consists of two transmission-type detectors which have good timing properties, such as timing detectors made of micro-channel plates [6]. Two timing detectors, each using a pair of micro-channel plates with a diameter of 45 mm, are installed to provide start and stop signal along a flight path with a typical timing resolution 120 ps. The stop detector is placed at 40 cm from the focal plane. In test experiment described in Section III, the start detector was set at 40 cm from the target. However, the start detector can be placed closer to targets to reduce relative inaccuracy with a longer flight distance. Note that both MCP detectors, which define the geometrical solid angle for the entire spectrometer, can be replaced with a position-sensitive MCP to provide position information so that the track of the peojectile-like ions after magenetic focusing can be reconstructed. The energy resolution can be further improved by the ToF information of a specify particle. Fig. 2 shows the result of offline test in a short flight distance of 5 mm, using a standard α source.

To improve the energy resolution for experimental demands, a special IC with a tranverse electric field has been designed. Conventional ionization chambers and active target time projection chambers [7, 8] are for references for special design of the ionization chamber. The IC is constructed from printed circuit boards with dimensions of 300 mm $\times$ 200 mm $\times$ 200 mm, locating at the focal plane. The length of 300 mm provides a broad energy range for Z identification. The circular entrance window of the IC, which is 100 mm in diameter, is positioned 18.3 cm away from the second ToF detector and is equipped with a 2 μm thick mylar foil. A large area of entrance window provides a large acceptance for energy measurement. The grid consists of gold-plated tungsten wires with a radius of 0.08 mm, soldered 1 mm apart. The distance from grid to anode is 22 mm, while the spacing between grid and cathode is 136 mm. 67 equipotential rectangle shaped loop electrodes are evenly distributed along the plate, with resistors of 1 MΩ to connect two adjacent electrodes.

This IC is designed with three-dimensional position resolution capabilities, allowing for precise $\Delta E - E$ and position detection. The energy resolution can be improved by the track reconstruction given by the IC. Fig. 3 shows some details of the design.

The anode of IC is divided into seven sections, which can provide not only the energy loss ΔE and residual energy E_{R}, but also the trajectory (Z-direction) of the entrance ion. Each section is divided into two wedge-shaped parts to determine the X-position by the charge division method. The Y-position is provided by the drift-time difference between anode and cathode. The timing signal of MCP2 is also used for the reference of the drift-time measurement. Typical X, Y, and Z position resolutions are about 1.0, 0.5 and 2.0 mm, respectively, primarily depending on the properties of entrance ion, the working gas as well as the high voltage supplied. The

smart preamplifier (SPA) [9] is used for the signal readcout of IC. Fig. 4 shows the result of offline test, using a fission source ^{252}Cf. The fission fragments of this source have a continuous energy spectrum. The working gas is 99.9% pure propane with a pressure of 30 torr. The operating voltage is 110 V for the anode and -308 V for the cathode.

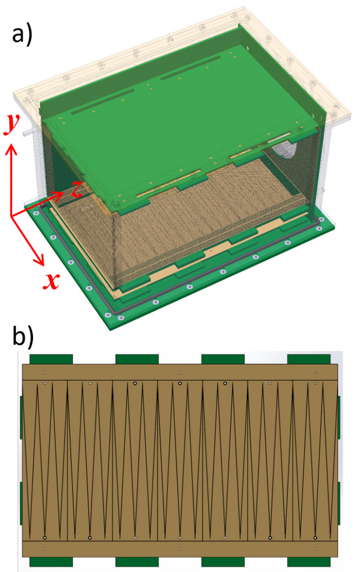


Fig. 3. (Color online) Schematic view of a) IC and b) its anode.

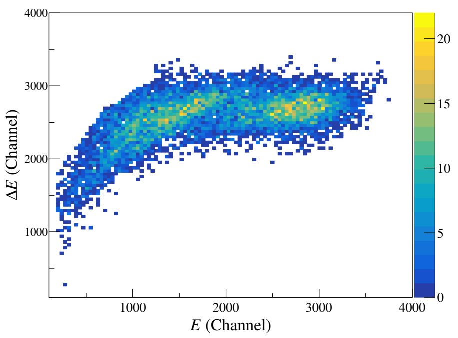


Fig. 4. (Color online) $\Delta E - E$ spectrum obtained by a ^{252}Cf fission source.

Practical flight distances are constrained for many technical reasons, especially solid angle considerations [10]. Because of the optical focusing by the quadrupole triplet lens, the real flight distance of the projectile-like particles may deviate from the designated length between start and stop detectors. For this reason, the X-Y position information at the focal plane and the trajectory of the entrance ion provided by IC could be used to correct the flight distance, so that the relative inaccuracy of the ToF measurement is partly reduced.

B. The ion-optical system

The ion-optical system is designed to use quadrupole triplet lens (Q1-Q2-Q3) to transport the entrance ions to the focal plane, which is about 2.70 m away from the target. Three quadrupole magnets Q1, Q2 and Q3 are equipped at 0.85, 1.35, 1.85 m from the target. The Q1 and Q3 quadrupoles have the same structure with an aperture of Φ_{ape} = 100 mm and maximum magnetic flux density B_{max} = 0.373 T. The Q2 quadrupole locates in the middle, with a reverse-phase current, has an aperture Φ_{ape} = 130 mm and a maximum magnetic flux density of B_{max} = 0.636 T. Ions with a magnetic rigidity up to $B\rho = 0.95$ Tm can be analyzed in the maximum angular acceptance $\Delta\theta = 3.3°$ and $\Delta\phi = 7.3°$.

The HiToF spectrometer can be operated in three modes: a) both X and Y focusing (double-focusing), b) X focusing and Y parallel, and c) X parallel and Y focusing. The double-focusing operation mode, which provides the maximum solid angle, enhances the transmission efficiency, and mode c) offers a method to preserve the information of the scattering angle by focusing only perpendicular to the reaction plane [3, 10]. The solid angle of the spectrometer was confirmed through the measurement of the yield of all quasi-elastic events on the focal plane, as a function of the quadrupole field.

The corresponding ion trajectories calculated by GICOSY code [11] are shown in Fig. 5. The setting of the quadrupole triplet lens is mainly determined by the mass, energy and charge state of the entrance ion.

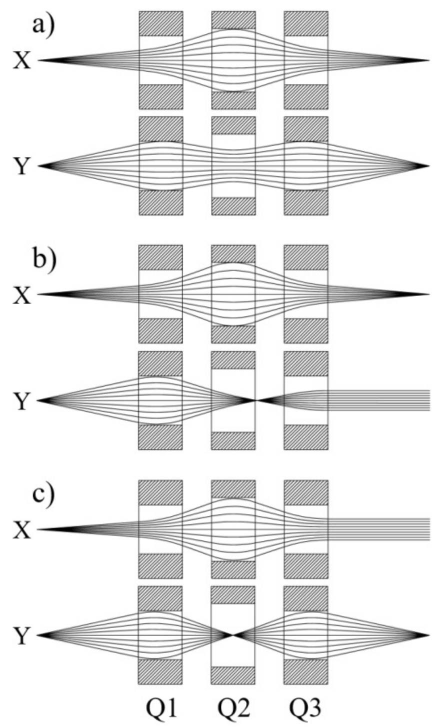


Fig. 5. Ion trajectories of the HiToF spectrometer in three operating modes: a) both X and Y focusing (double focusing), b) X focusing and Y parallel, and c) X parallel and Y focusing.

III. PERFORMANCE OF HITOF

An experiment of ^{32}S + ^{90,94}Zr at $E_{\rm Lab}$ = 135 MeV (about 15% above the Coulomb barrier) has been conducted on the spectrometer in order to test its performance. Two targets consist of ^{90}ZrO$_2$ and ^{94}ZrO$_2$ evaporated onto 25 μg/cm^2 carbon backings with thicknesses of 104 μg/cm^2 and 120 μg/cm^2 respectively. Focusing performance of magnets, performance of detection system and the capability of particle identification were tested in the experiment.

The transmission efficiencies were determined by measuring the product ions on the focal plane with and without magnetic fields. The magnetic fields for maximum transmission efficiencies B_0 were set based on GICOSY calculations. Several magnetic fields close to B_0 were tested as well. As shown in Fig. 6, the enhancement factors of yield ratios with and without quadrupole fields for charge states of 11$^+$, 12$^+$ and 13$^+$ in the double-focusing operating mode were in good agreement with GICOSY calculations for different magnetic fields. In this case, the magnetic field setting for the maximum transmission efficiency is $B_{\rm Q2}/B_{\rm Q1}$ = 1.678 with $B_{\rm Q1}$ = $B_{\rm Q3}$.

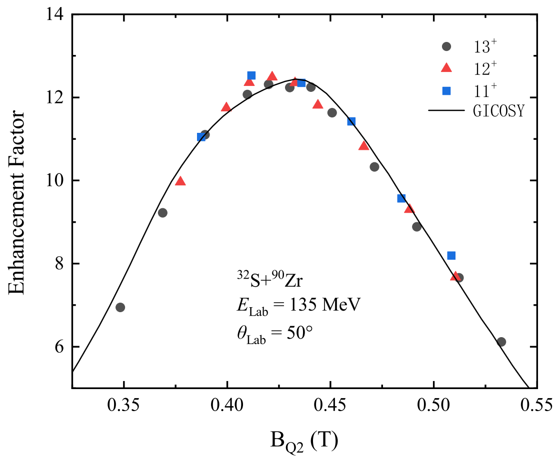


Fig. 6. (Color online) Enhancement factors provided by yield ratios varying with the Q2 field for different charge states. The solid line represents the GICOSY calculation.

In the experiment, the ToF was measured between two MCP detectors at a flight distance of 1.9 m. The ToF measurement is influenced by a number of factors such as spectrometer isochronism, target thickness inhomogeneity, energy straggling in the target, imperfect software corrections and finite resolutions of the ToF detectors [5]. As shown in Fig. 7, the FWHM of the main peak of the particle ^{32}S without magnetic field is 500 ps. The ToF of focused ions is also affected by the uncertainty in the flight distance due to the large solid angle.

Different magnetic fields are required for particles with different energies, masses and charge states. Additionally, three operating modes of focusing were also tested.

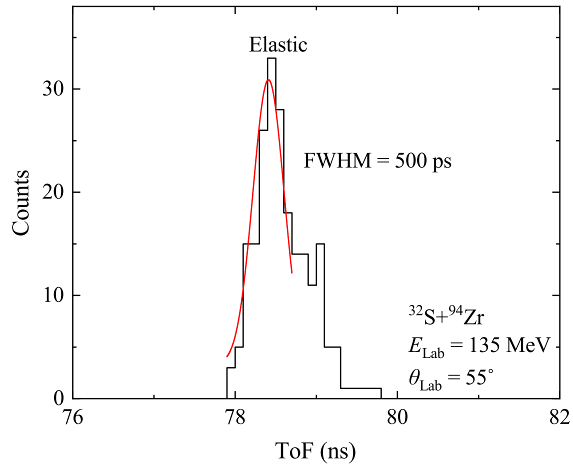
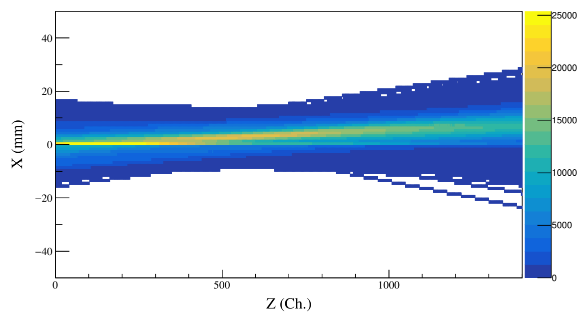
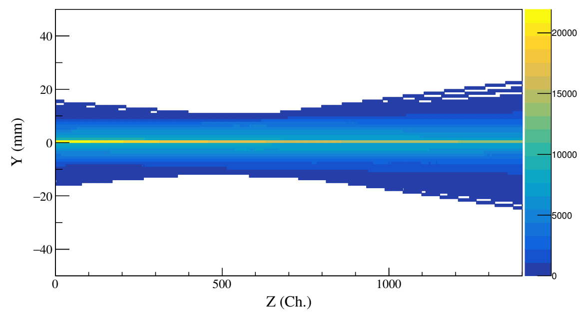


Fig. 7. (Color online) ToF spectrum of ^{32}S elastic scattering from ^{94}Zr target.



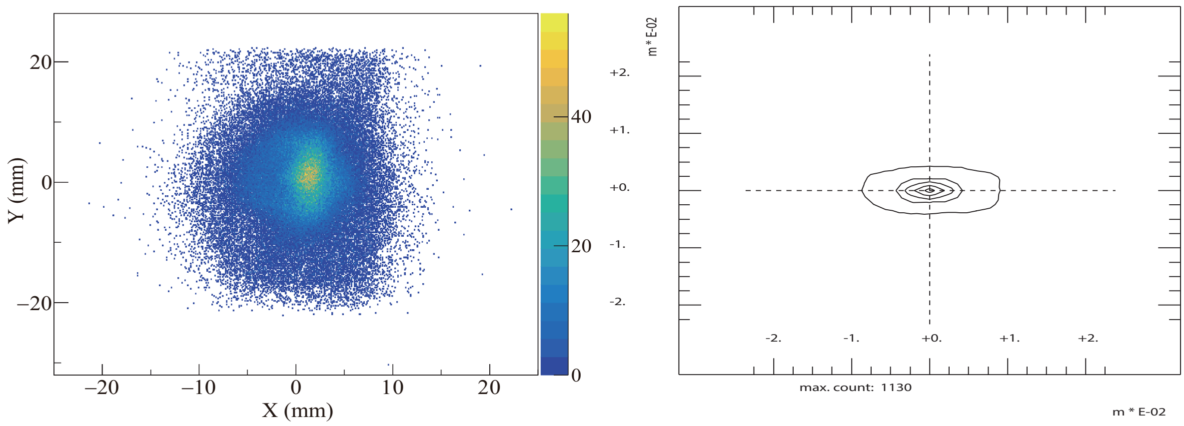
(a) trace on the XZ plane



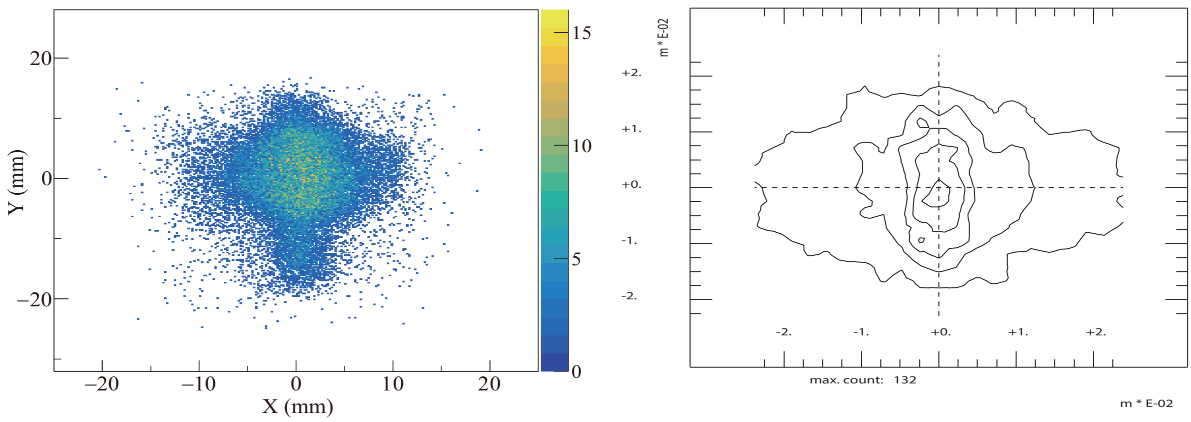
(b) trace on the YZ plane

Fig. 8. (Color online) Tracking results of IC in double-focusing mode for the reaction system ^{32}S + ^{94}Zr at $\theta_{\rm Lab}$ = 55°. (a) trace on the XZ plane (b) trace on the YZ plane.

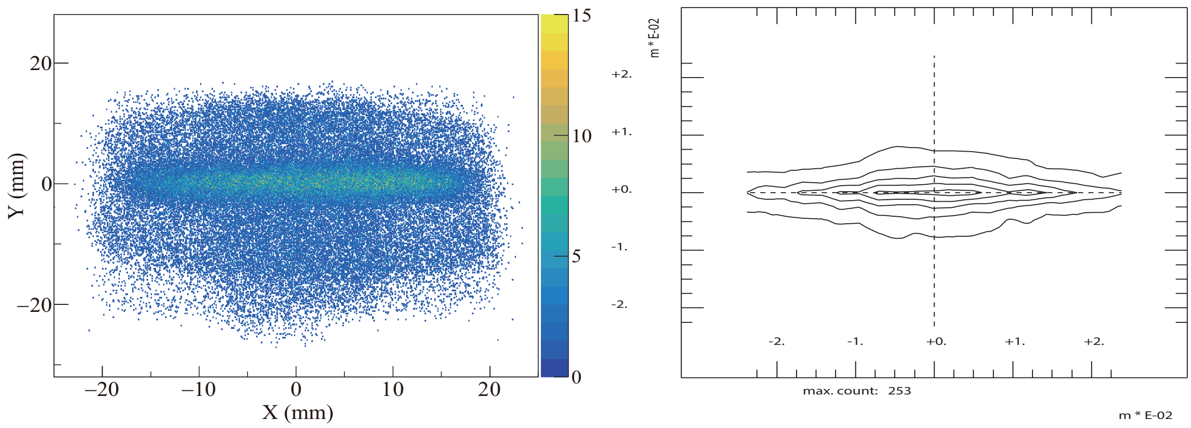
For the test experiment, we redistributed the seven sections of the IC anode into three parts of two, two and three sections respectively. Propane was used as the working gas for ionization within a pressure range from 50 to 70 torr. In Fig. 8 we show the tracking results provided by IC, which is useful



(a) Double-focusing mode



(b) Y parallel - X focusing mode



(c) X parallel - Y focusing mode

Fig. 9. (Color online) Comparison of X-Y distributions for three focusing modes and GICOSY calculation results, for the reaction system ^{32}S + ^{94}Zr. (a) X-Y distribution on focal plane for double-focusing mode at $\theta_{\mathrm{Lab}} = 55^{\circ}$ with ic pressure 60 torr (b) X-Y distribution on focal plane for Y parallel - X focusing mode at $\theta_{\mathrm{Lab}} = 50^{\circ}$ with ic pressure 50 torr (c) X-Y distribution on focal plane for X parallel -Y focusing mode for reaction system at $\theta_{\mathrm{Lab}} = 50^{\circ}$ with ic pressure 50 torr. For different focusing mode, the left penal is position spectra on the focal plane, given by IC. The right panel is GICOSY calculation results under the corresponding condition.

for more precise energy detection. Through the method described in section II, the images of X-Y distributions on the

focal plane for three focusing modes are shown in Fig. 9, which were consistent with the distribution results calculated by GICOSY. In this case, the magnetic field setings B_{Q2}/B_{Q1} of different focusing modes (a), (b) and (c) are 1.678, 1.32 and 1.577 respectively, with $B_{Q1} = B_{Q3}$ at the same time. The results of Fig. 9 verify the position resolution capability of IC and the focusing performance of quadrupole triple lens.

The large effective solid angle and good charge and mass resolution provide opportunities for measuring cross sections of weak reaction channels. The $\Delta E-E$ measurement, shown in Fig. 10, identifies different elements precisely. The populated products isotopes at E_{beam} = 135 MeV precisely extend from Z = 12 (4 proton stripping) to Z $\leq$ 16. The lower energy particle observed were elements C (Z = 6) and O (Z = 8) on the targets and their backings.

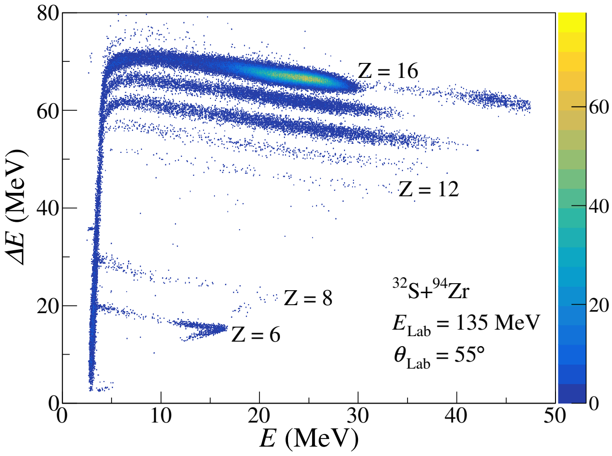


Fig. 10. (Color online) $\Delta E - E$ matrix at θ_{Lab} = 55°. Different charges of projectile-like nuclears are clearly separated.

The resolution of HiToF spectrometer allows an unambiguous identification of numerous projectile-like products. Mass-charge two dimensional spectra were obtained for the reaction ^{32}S + ^{90,94}Zr at θ_{Lab} = 55° (close to the grazing angle), as shown in Fig. 11. A number of reaction channels, including proton stripping, neutron stripping and neutron pick-up reaction are measured. Reaction products were clearly identified up to the pick-up of two neutrons and stripping of four protons. Rare events belonging to the -5p channels were also observed.

For the reaction system, IC provides a nuclear charge resolution $\Delta Z/Z = \frac{1}{50}$. The mass resolution achieved was σ = 0.2 amu, which is mainly limited by the energy resolution of IC.

Mass spectra for various Z selections are shown in Fig. 12 and Fig. 13. For Z = 16, an exponential decline of the ion yield with an increasing number of transferred neutrons can be observed. In Fig. 13, a number of channels from Z = 12 to Z = 15 are measured clearly. The peak with Z = 12, A= 26 corresponds to the -4p-2n channel.

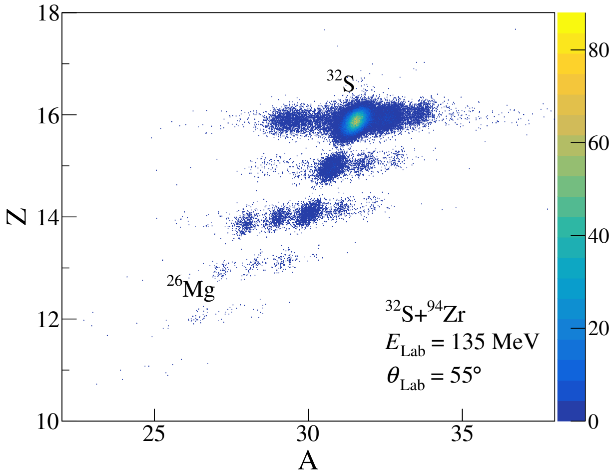


Fig. 11. (Color online) Z-A matrix at θ_{Lab} = 55° . The most intense spot at Z = 16 corresponds to A = 32. The resolving power of HiToF facilitates the clear and definitive identification of a diverse array of projectile-like reaction products.

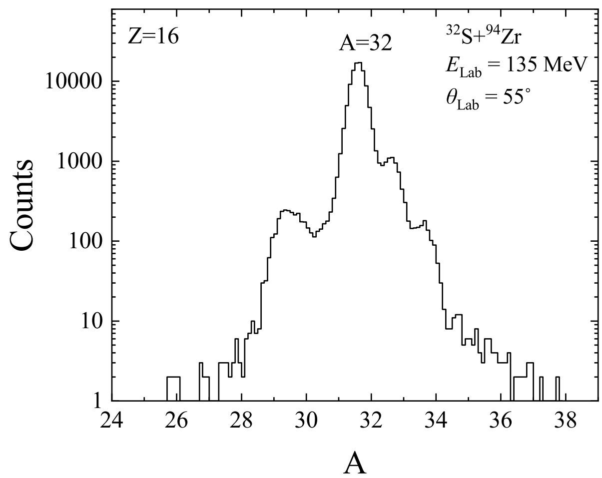


Fig. 12. Mass spectrum for S isotopes populated in the reaction ^{32}S (beam) + ^{94}Zr at θ_{Lab} = 55°

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IV. SUMMARY AND OUTLOOK

According to the test experiment, the HiToF spectrometer, a simple and high-precision equipment which can provide a large solid angle of 20 msr and allow a good resolution for mass, energy and position, has been adequately prepared to study multi-nucleon transfer reaction. The resolution of mass, charge and position reach σ = 0.2 amu, $\Delta Z/Z = \frac{1}{50}$, 1.0, 0.5 and 2.0 mm for X, Y and Z dimension, respectively. Different focusing modes of the quadrupole triplet lens provide possibilities for various investigations. The energies and/or masses can be investigated mainly limited by the resolving

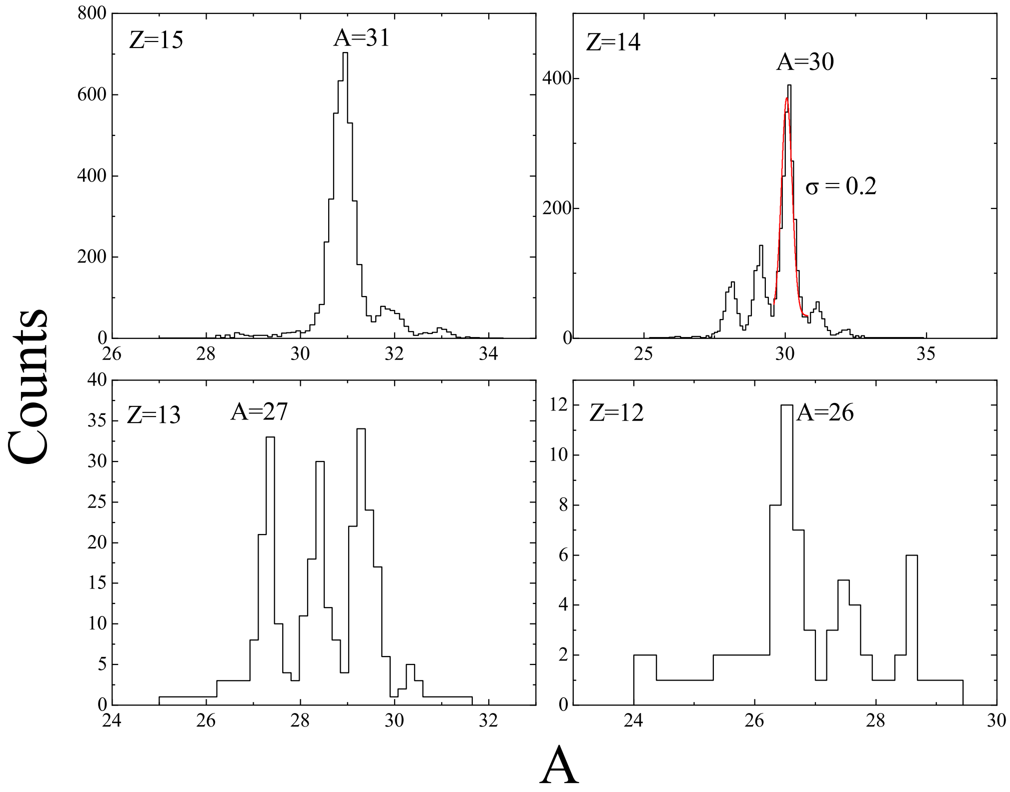

Fig. 13. (Color online) Projections on the mass matrix in ^{32}S (beam) + ^{94}Zr shown in Fig. 11, for different Z selections. The mass resolution is $\sigma = 0.2$

power of the detection system, which fundamentally determines the performance of the spectrometer.

In the near future, the improved IC and the track reconstruction via the timing detector of ToF measurement and IC are would be combined to enhance the energy resolution with more precise magnetic field. An angle-distribution with higher precision would be given via the coincidence of IC for measurement of projectile-like particles and *v*-*E* detector for measurement of target-like particles.

For the field of low energy nuclear reaction, HiToF provides good opportunities for reaction mechanisms study experimentally. Superior performances of the device are required for frontiers, therefore some efforts will be made to improve the detection system such as enhancement of energy and position resolution.

[1] L. Corradi, A. M. Stefanini, C. J. Lin et al., Multinucleon transfer processes in ^{64}Ni+^{238}U. Phys. Rev. C **59**, 261 (1999). doi: 10.1103/PhysRevC.59.261

[2] T. Niwase, Y. X. Watanabe, Y. Hirayama et al., Discovery of New Isotope ^{241}U and Systematic High-Precision Atomic Mass Measurements of Neutron-Rich Pa-Pu Nuclei Produced via Multinucleon Transfer Reactions. Phys. Rev. Lett. **130**, 132502 (2023). doi: 10.1103/PhysRevLett.130.132502

[3] R.R. Betts, Time of flight detectors for heavy ions. Nucl. Instrum. Methods **162**, 531 (1979). doi: 10.1016/0029-554X(79)90731-6

[4] L. Corradi, G. Montagnoli, D. R. Napoli et al., A kinematic coincidence technique for the study of low-energy heavy-ion reactions. Nucl. Instrum. Methods A **297**, 461 (1990). doi: 10.1016/0168-9002(90)91330-E

[5] G. Montagnoli et al., The time-of-flight spectrometer for heavy ions PISOLO. Nucl. Instrum. Methods A **454**, 306 (2000). 10.1016/S0168-9002(00)00482-4

[6] W. Starzecki, A.M. Stefanini, S. Lunardii et al., A compact time-zero detector for mass identification of heavy ions. Nucl. Instrum. Methods **193**, 499 (1982). doi: 10.1016/0029-554X(82)90242-7

[7] Wu, HK., Wang, XY., Wang, YM. et al. Fudan multi-purpose active target time projection chamber (fMeta-TPC) for pho-

tonuclear reaction experiments. NUCL SCI TECH 35, 200 (2024). doi: 10.1007/s41365-024-01576-1

[8] Tian, J., Sun, ZP., Chang, SB. et al. Studies of an event-building algorithm of the readout system for the twin TPCs in HFRS. NUCL SCI TECH 35, 73 (2024). 10.1007/s41365-024-01434-0

[9] Wang, DX., Lin, CJ., Yang, L. et al., Compact 16-channel integrated charge-sensitive preamplifier module for silicon strip detectors. NUCL SCI TECH 31, 48 (2020). doi: 10.1007/s41365-020-00755-0

[10] R. Bass, J.v. Czarnecki and R. Zitzmann, Design study of a magnetically focussed time-of-flight spectrometer for heavy ions. Nucl. Instrum. Methods **130**, 125 (1975). doi: 10.1016/0029-554X(75)90164-0

[11] M. Berz, H. C. Hoffmann, H. Wollnik, et al., COSY 5.0 - The fifth order code for corpuscular optical systems. Nucl. Instrum. Methods A **258**, 402 (1987). doi: 10.1016/0168-9002(87)90920-X.